Daly, Reginald Aldworth
Origin of the iron
ores at Kiruna

QE
381
F5D35

Sweden

VETENSKAPLIGA OCH PRAKTISKA UNDERSÖKNINGAR I LAPPLAND
ANORDNADE AF LOUSSAVAARA—KIIRUNAVAARA AKTIEBOLAG

GEOLOGY OF THE KIRUNA DISTRICT
5

ORIGIN OF THE IRON ORES
AT KIRUNA

LIBRARY
NOV 11 1968
UNIVERSITY OF TORONTO

BY

REGINALD A. DALY
HARVARD UNIVERSITY

NORDISKA BOKHANDELN
STOCKHOLM

#404

Digitized by the Internet Archive
in 2008 with funding from
Microsoft Corporation

http://www.archive.org/details/originofironores00dalyuoft

VETENSKAPLIGA OCH PRAKTISKA UNDERSÖKNINGAR I LAPPLAND
ANORDNADE AF LOUSSAVAARA—KIIRUNAVAARA AKTIEBOLAG.

GEOLOGY OF THE KIRUNA DISTRICT
5

ORIGIN OF THE IRON ORES AT KIRUNA

BY

REGINALD A. DALY
HARVARD UNIVERSITY

NORDISKA BOKHANDELN
STOCKHOLM

QE
381
F5D35

STOCKHOLM 1915
KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER
150965

LEGENDS FOR FIGURES.

Figure 1. Geological map of the Kiruna district (after H. Lundbohm, Geol. Fören. Förh., Stockholm, 1910).

Figure 2. Schematic cross-section through Kiirunavaara, just south of the lake at Kiruna. *1*, Soda-greenstone. *2*, Kurravaara conglomerate. *3*, Syenitic body. *4*, Iron ore. *5*, Quartz porphyry body. *6*, Hauki complex. *7*, Amphibolite. *8*, Quartz porphyry of the Tuolluvaara type.

Figure 3. Schliers of magnetite in quartz porphyry, east of Direktören, Kiirunavaara (after P. Geijer, p. 148 of his memoir). Shows angular forms in endogenous growths of iron ore.

Figure 4. Various ore inclusions in the main quartz porphyry; showing angular forms due to resorption. Inclusion No. 1 is seen to have been just separated into two parts. No. 3 seems to have suffered still more advanced division. The small white spots in Nos. 1 and 4 represent feldspar phenocrysts and inclusions of the porphyry ground-mass. No. 5 is a very rough sketch of an inclusion in a specimen on exhibition at the Museum of the Geological Bureau, Stockholm. The localities are: for Nos. 1 and 2, power-house, Kiruna; for No. 3, base of quartz porphyry on Luossavaara; for No. 4, three meters from contact with Hauki complex, street in Kiruna; for No. 5, unknown.

CONTENTS.

Page.

The problem . . . . 5.
Principal formations of the Kiruna district . . . . 6.
Relations among the Kurravaara and Hauki complexes and the porphyries . 11.
Eruptive sequence in the Kiruna district . . . . 14.
Differentiation of the main ore bodies . . . . 16.
Ore "inclusions" in the quartz porphyry . . . . 19.
Concentration of the units of differentiation . . . . 26.
Comparison of the syenitic and quartz porphyry magmas . . . . 27.
Distribution of densities in the two laccoliths . . . . 28.
Special conditions for the development of the Kiruna ore bodies . . . . . 29.
Summary . . . . 29.

The Problem.

The magnetite of Kiirunavaara is said to form the largest high-grade body of iron ore now being worked in any country. Its economic importance for Sweden and for the world will insure widespread, continuous attention for this deposit. Yet the ore body deserves its growing fame also because of its meaning for the pure science of rocks. Whatever be the final solution to the genetic problem, this ore mass, like the neighbouring one on Luossavaara, must always hold a leading place in the thought of the petrologist. At present the ore bodies are generally ascribed to magmatic differentiation rather than to pneumatolytic or other processes.[1] Agreement to that extent has been reached through the concordant testimony of Geijer, Högbom, Stutzer, Lundbohm, and others, who have embodied the results of field, microscopic, and chemical studies in a number of memoirs dealing with the Kiruna district. Basing his work on Lundbohm's thorough mapping of that region, Geijer has written a detailed account of its minerals and rocks which is deservedly noted as a classic in petrography. A careful reading of Geijer's monograph should convince anyone of the correctness of the view that the Kiruna ores are magmatic differentiates. The exact mechanism of the differentiation is, however, a residual problem for which Geijer offered a tentative solution not so generally accepted, nor did Geijer himself offer it without due reserve. For general geology the discovery of the mechanism of magmatic splitting is more important than even the proof that differentiation has occurred in a given case. Full faith in the differentiation itself often comes only after a vision of the actual mechanism. In

[1] For a résumé of the older theories, including the suggestion of a pneumatolytic origin by Bäckström and De Launay, see Geijer's »Igneous Rocks and Iron Ores of Kiirunavaara, etc.», Stockholm, 1910, p. 253. True pneumatolytic action has doubtless played an essential part in the formation of small bodies of hematite, magnetite, and apatite in the Hauki complex, as well as in the formation of the apatite dikes or veins cutting the upper part of the quartz porphyry. This conclusion principally rests on Geijer's detailed petrography and is identical with his view. Nevertheless, it does not follow that the main ore bodies have the same origin, and the writer believes the objections to the pneumatolytic hypothesis for these greater masses at the base of the quartz porphyry to be insuperable. Pneumatolysis was here of minor, unessential importance, just as it was in the concentration of sulphide ores at Sudbury, Ontario.

fact, the very idea of differentiation must be vague in proportion to one's ignorance of the concrete processes involved.

Stimulated by the writings of the authors mentioned, as well as by personal letters from Dr. Geijer and Dr. Lundbohm, the writer journeyed to Kiruna and spent nine days of August, 1914, in a field study of the region. Though the time was short, it sufficed for the special investigation of a principal point in the geology of the ore bodies, and for securing personal acquaintance with the formations so admirably described by Geijer and Lundbohm. The particular investigation concerned the nature and origin of the numerous small »inclusions» of iron ore scattered through the porphyry, which forms the hanging wall of the ore bodies at both Kiirunavaara and Luossavaara. As a result, the writer was led to conclude that all, or nearly all, of such »inclusions» are direct segregations from the porphyry magma and not foreign fragments, or xenoliths, as held by Geijer, Stutzer, and others. This and other facts support the much more important conclusion that the main ore bodies are of origin contemporaneous with the hanging-wall porphyry and have settled out on the floor of the porphyry magma. In other words, the main ore at Kiruna is regarded as one pole of a gravitative splitting *in situ*.

In a personal letter, Dr. Geijer remarks that he also entertained that hypothesis of origin at an early stage in his long investigation, but was forced to abandon it for certain reasons, to be noted on a later page. His objections do not seem convincing to the present writer, who believes that this explanation of the ore accords best with the multitude of facts presented in Geijer's book. In the following discussion of ore genesis a brief summary of the geology and petrography of the Kiruna region is introduced as a convenient aid in marshalling the data.

The writer's hearty thanks are due to Dr. Hjalmar Lundbohm for his hospitality in Kiruna and for his active sympathy during the field investigation, in which the writer was also aided by Dr. G. T. Lindroth, who acted as guide in the district and won the writer's gratitude for that service.

Principal Formations of the Kiruna District.

The accompanying map and section are taken from the writings of Lundbohm and Geijer. These diagrams will facilitate a review of the structure of the district. (Figures 1 and 2.)

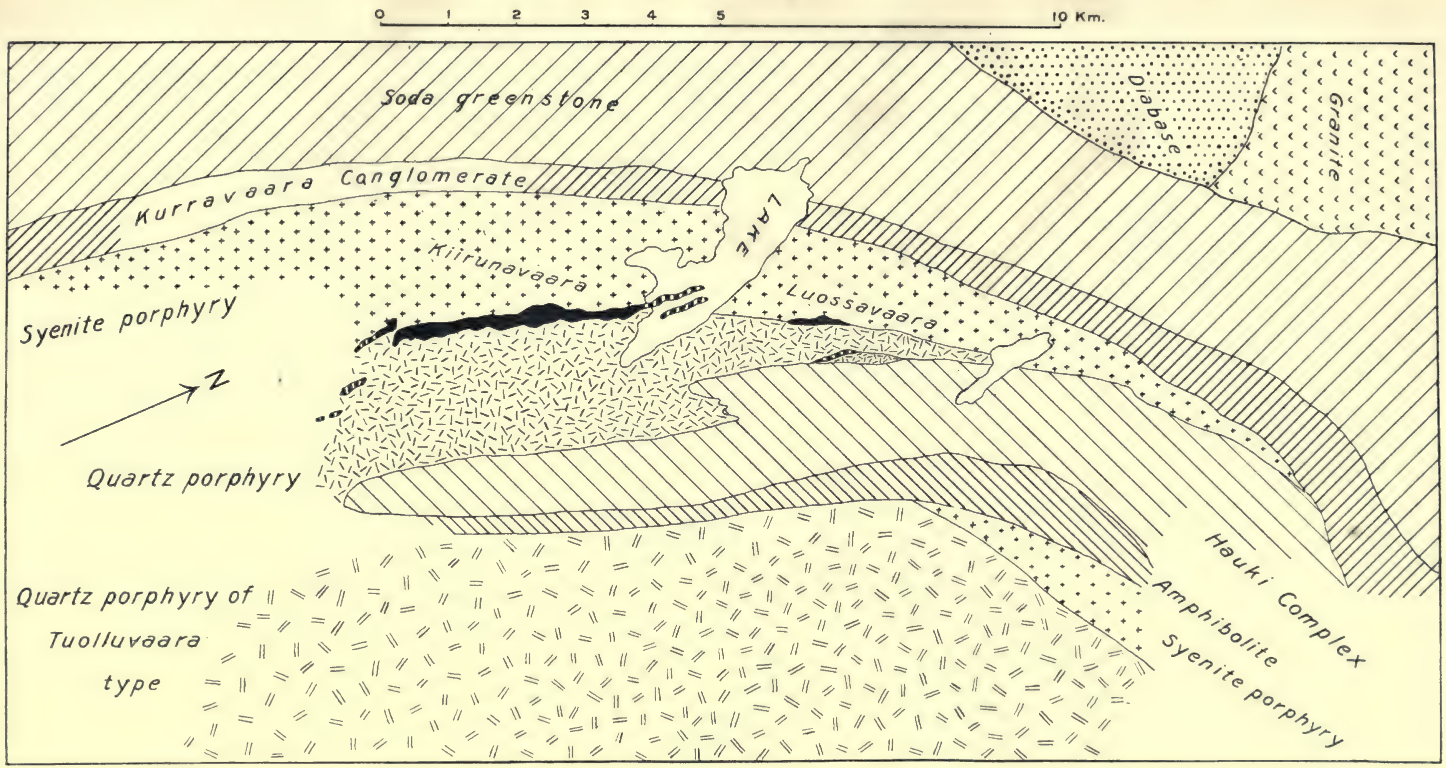
0
1
2
3
4
5
10 Km.
Soda greenstone
Diabase
Granite
Kurravaara Conglomerate
LAKE
Kiirunavaara
Luossavaara
Syenite porphyry
N
Quartz porphyry
Hauki Complex
Amphibolite
Syenite porphyry
Quartz porphyry of
Tuolluvaara
type

Figure 1.

In general, the rocks form a monoclinal mass, dipping steeply to the eastward. The oldest formations shown on the maps of the district so far published, are granite and diabase (Analysis in Col. 1 of Table I), no detailed description of which has yet been given. Then, in succession from west to east, the rocks occur in groups named as follows: the Kurravaara complex, a syenite-syenite porphyry band, the Kiirunavaara-Luossavaara ore bodies, the main quartz porphyry formation, and the Hauki complex. In this list the names »syenite porphyry» and »quartz porphyry» are adopted from the recent memoirs on the Kiruna region, though these names, especially the latter, are not very successful in conveying a proper idea of the corresponding rocks.

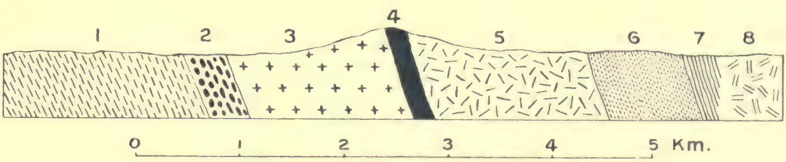

Figure 2.

Table I, showing average analyses of principal rock-bodies.

	1. Diabase of the Kiruna district.	*2.* Soda-greenstone.	*3.* Syenite.	*4.* Syenite porphyry.	*5.* Whole syenitic body.	*6.* Quartz porphyry.	*7.* The main ore bodies.
No. of analyses averaged .	1	2	2	3	5	4	14
SiO_2	50.46	52.90	56.44	60.60	58.94	69.41	2.08
TiO_2	0.60	1.37	1.81	1.22	1.45	0.38	0.31
Al_2O_3	20.08	14.20	14.67	16.21	15.59	13.92	0.99
Fe_2O_3	2.00	3.15	8.21	3.79	5.56	3.33	65.32
FeO	5.56	8.99	2.95	2.26	2.54	1.52	25.85
MnO	0.10	0.14	0.21	0.22	0.22	0.04	0.26
MgO	6.27	3.82	2.21	2.03	2.10	0.64	0.69
CaO	10.33	7.31	3.90	3.91	3.90	0.89	2.99
Na_2O	3.56	5.72	6.20	6.28	6.25	5.49	—
K_2O	0.68	0.70	2.73	2.87	2.81	3.08	—
H_2O	0.60	0.96	0.55	0.54	0.56	0.69	—
P_2O_5	0.12	0.07	0.22	0.19	0.20	0.05	1.71
S	0.03	0.04	0.01	—	—	0.02	0.01
CO_2	—	0.64	—	—	—	0.52	—
	100.39	100.01	100.11	100.12	100.12	99.98	100.21

The *Kurravaara complex* is composed of two conformable members. The lower one is mapped as soda-greenstone, otherwise described by Lundbohm as syenite porphyry rich in dark-coloured minerals. Albite and hornblende are the chief constituents. Some abnormally salic phases represent transitions into syenite porphyry similar to the formation making contact with the Kurravaara complex on the east. In some places the soda-greenstone is dioritic. The average of two analyses of the normal greenstone is given in Col. 2 of Table I. This band varies from $2{,}_5$ to $8{,}_0$ kilometers in width.

Overlying the soda-greenstone is the second nember, the »Kurravaara conglomerate», a mass of alternating pebble-rich and pebble-free beds, which Lundbohm, Geijer, and their colleagues regard as volcanic tuffs. The pebbles are composed of dense syenite porphyry, medium-grained syenite, quartz porphyry tuff, massive and tuffaceous soda-greenstone, pure magnetite, mixtures of apatite and magnetite, quartzite, striped jasper, and crystalline limestone.

The *syenitic body*, adjoining the Kurravaara complex, shows two phases. On the west (toward its lower contact) the rock is a massive, medium-grained syenite, typically carrying 65 per cent. of perthitic feldspar, 15 per cent. of augite, 10 to 15 per cent. of magnetite, and smaller amounts of titanite and apatite, with a little quartz. The grain of the rock is shown in the average diameters of the feldspars, namely 5 to 6 millimeters. Sometimes the syenite consists of little else than the perthitic feldspar and magnetite. Schliers of magnetite occur; these usually show sharp contacts with the rest of the rock.

On the east side, the syenite passes with rapid transitions into the second phase, a syenite porphyry. Chemically the two phases are nearly identical; they are separated on the basis of difference in texture. The phenocrysts of the porphyry are perthitic feldspars ranging from 1 mm. to 10 mm. in diameter. The ground-mass varies from that of a medium-grained syenite to that of a rock dense to the naked eye. In no case has a glassy base been observed. Concretionary nodules of hornblende, apatite, magnetite, or biotite, and schliers of magnetite occur in the porphyry. Occasionally feldspar is found in these segregations. Some phases carry as much as 30 per cent. of magnetite, by weight. The concretions are often surrounded by light-coloured aureoles or shells, suggesting that they have been differentiated from the mass in which they are enclosed.

The averages of two analyses of the syenite, of three of the syenite porphyry, and of all the five are given in Cols. 3, 4, and 5 in Table I.

The *Kiirunavaara and Luossavaara ore bodies* are practically identical in petrographic characters. The ore is magnetite, generally mixed with apatite, ranging from about $0,_{16}$ to about $27,_{0}$ per cent. of the ore. Small amounts of pyroxene, uralite, tourmaline, talc, asbestus, rutile, and titanite are sometimes found. The average of fourteen analyses of the ore is given in Col. 7 of Table I.

The Kiirunavaara body is 3,000 meters long, with an average width of 96 meters at the present erosion surface, and an average thickness of about 78 meters. As the map shows, the body is lenticular; its greatest thickness is 164 meters. Its total area, as exposed and inferred from magnetic exploration, is 436,000 square meters. The Luossavaara body is 1,200 meters long and 50 meters wide at the maximum.

Like the syenite and syenite porphyry, the main *quartz porphyry* is massive and only locally sheared. Its phenocrysts are never quartz but are reddish feldspars ranging in diameter from 1 mm. to 15 mm. as the approximate average. The ground-mass is microgranitic or micropoikilitic, seldom spherulitic; no glassy phase is reported. Quartz makes up 15 to 25 per cent. of the ground-mass. Magnetite is relatively abundant, sometimes composing 10 per cent. of the rock by weight. The average of four analyses of this porphyry is shown in Col. 6 of Table I.

The *Hauki complex* is described as made up of three members, the oldest on the west, as usual. The latter is composed of silicified tuffs, enclosing beds of igneous rocks; also sericite schists and strongly schistose lavas. In the tuffs are local, thin lenses of iron ore, which is regarded as largely contemporaneous with its tuffaceous matrix. The igneous rock interbedded with the tuffs is a more or less schistose »syenite porphyry», which is often amygdaloidal or agglomeratic.

The second, next younger, part of the complex is a mass of conglomerate and greywacke overlaid by well-cleaved phyllite. Among the pebbles of the conglomerate are quartzite, syenite porphyry, quartz porphyry and water-worn hematite.

The top member is much the thickest. It is a quartzitic sandstone, with interbeds of conglomerate rich in pebbles of quartz porphyry and of syenite porphyry, like those in the beds of the middle member. This sandstone is stated to be composed of quartz to the extent of 70 to 75 per cent. of its weight.

Ascertained structural relations.

The geologists who have studied the Kiruna district, in general agree that the Kurravaara soda-greenstone and the younger, overlying conglomerate represent a volcanic series of great thickness; and that much of the Hauki complex is of similar origin. There is, further, complete agreement: first, that the syenite and syenite porphyry are contemporaneous parts of one igneous body and are older than the main quartz porphyry; secondly, that the Kiirunavaara and Luossavaara ore-bodies are younger than the syenite porphyry but nearly contemporaneous with the quartz porphyry.

There is less perfect agreement regarding the other important relations, namely: that between the Kurravaara and Hauki complexes; that between the porphyry bodies and the two complexes; and, of course, the exact relation between the ore bodies and the quartz porphyry. The first two sets of relations really offer one problem and may be considered together.

Relations among the Kurravaara and Hauki Complexes and the Porphyries.

Geijer thinks it probable that the syenite-syenite porphyry body represents a gigantic extrusion of lava wich flowed ower the Kurravaara complex; that the quartz porphyry is a similar extrusive lava somewhat younger than the syenitic body; and that the Hauki complex is essentially a fragmental, volcanic mass overlying, and thus younger than the quartz porphyry.

Stutzer's less detailed but suggestive paper carries the conclusion that the porphyries are essentially contemporaneous and both intrusive («Gangporphyre») into the Kurravaara complex and into the two older members of the Hauki complex; though he thinks that the thick, quartzitic sandstone of the Hauki complex is really separated from the quartz porphyry by an erosion surface. In this latter point, Zenzén, who is to publish a special monograph on the Hauki rocks, agrees with Stutzer. During the writer's brief visit to the region he made certain observations which tend to sustain belief in this unconformity.

Of the two views the writer believes that the intrusion hypothesis is preferable. This it not the place to go into all the evidence, for it will be seen that the favored explanation of the ore bodies is practically independent of this question. Yet a few points may be noted.

At the well exposed contact between the Hauki rocks and the quartz porphyry, in the streets of Kiruna, there is none of the usual signs of a lava surface. On the contrary, the porphyry there shows a massive, non-amygdaloidal phase of the kind normally appearing at dike or laccolithic contacts. Special search was made for vesicular, ropy, glassy, or other truly volcanic phases in the main porphyry bodies. None was found by the writer nor is any convincing case recounted in Geijer's memoir.

The matter has been further tested by a comparison of the porphyry at various horizons, from top to bottom. The hypothesis of extrusion demands that the ground-mass of the porphyry should be decidedly denser at the top of the body than elsewhere. The chilling of the magma at the base should be much less rapid and the grain of the ground-mass correspondingly coarser. The grain should be coarsest in the heart of the thick flow. Microscopic study has showed that the ground-mass in each of two quartz porphyry specimens, taken respectively at points about 2 and 3 meters from the upper contact, is actually coarser than the ground-mass in each of two specimens taken at points about 10 and 13 meters from the basal contact (with the Kiirunavaara ore body). In the first pair of specimens the quartz grains of the ground-mass range from less than 0.01 mm. to 0.1 mm.; in the second pair the range is from less than 0.01 mm. to 0.05 mm. Other thin sections show that the quartz grains of the ground-mass at various intermediate horizons, 500 meters or more from either contact, are seldom as much as 0.1 mm. in diameter, though the feldspars there form in vague, poikilitic individuals of somewhat larger size. In fact, as Geijer points out, the ground-mass of the quartz porphyry is in general »very fine-grained or most often dense», so that it is difficult to determine its constituent grains even with the highest powers of the microscope. Their determination is easier in occasional thin schliers of coarser grain, which occur at many horizons but are always subordinate in volume. The syenite porphyry is yet more schlieric, but the writer has found the grain of the ground-mass to be extremely fine and nearly constant, from the upper contact to a horizon at least 300 meters stratigraphically below that contact. These facts render it highly improbable that the compactness of the ground-mass in either porphyry body can be taken as an evidence of an extrusive origin.[1] The actual crystallinity and grain of each porphyry body are more likely to be explained by the chemical composition and

[1] Cf. P. Geijer. »Igneous Rocks and Iron Ores of Kiirunavaara, etc.» 1910, p. 135.

initial temperatures of the magmas than by chilling because of radiation of heat after eruption.

Largely owing to lack of exposures at critical places, there is difficulty in applying some of the ordinary criteria for intrusion. The agglomeratic masses isolated in the quartz porphyry on Luossavaara have not the normal field relations of pyroclastic beds in a volcanic pile. It is more probable that these masses are huge xenoliths; if so, their position in the porphyry suggest that they originated in the Hauki complex rather than in the Kurravaara complex. On the other hand, apophysal injections into the greatly altered Hauki rocks are not easily recognized. Some sheet-like layers of porphyry in the complex may be of that origin. As Geijer points out, the Hauki rocks have suffered much hydrothermal alteration at their contact with the main porphyry; that is, true contact metamorphism has affected the overlying series. It is conceivable that the observed effects may have been produced by the heat and gases residual in the thick porphyry, assumed to be extrusive and quickly covered by the Hauki beds. To the writer it seems more probable that this contact metamorphism is of an order demanding belief in the intrusion hypothesis. On the railway east of the town, phyllite crops out at a distance of about 25 meters from the main quartz porphyry. The former there shows no evidence of contact metamorphism. However, no conclusion as to their relative age can be drawn, for the phyllite may belong to the series above the unconformity postulated by Zenzén and Stutzer; and, secondly, the contact may be a faulted one.

It is not impossible that the quartz porphyry locally broke through to the earth's surface, but the writer has found no field evidence of this. An absolute decision on the question cannot now be reached on account of the great rarity of porphyry outcrops at or near the upper contact of that body. The one good exposure found by the writer seems to permit of no other conclusion than that the quartz porphyry is there intrusive. The complete absence of glassy and scoriaceous phases (the occasional miaroles are clearly not amygdules), the general »habit» of the porphyry, and especially the grain of the ground-mass are more general reasons supporting the intrusion hypothesis for both of the great porphyry bodies.

Without going further into detail, the writer's general conception of the confessedly obscure relations may be stated. For the sake of brevity a somewhat dogmatic form may be permitted. The Kurravaara complex and the pre-quartzite members of the Hauki complex originally formed a thick pile of volcanic material, chiefly pyroclastic. Into that pile the syenite-syenite porphyry body was injected as a large laccolith. Shortly after its consolidation, the quartz porphyry magma was injected, also laccolithically, along the roof contact of the syenite porphyry, which was still hot.

The Hauki and Kurravaara complexes are thus two parts of one conformable, bedded series which has been split by a »composite» laccolith, made up of two simple laccoliths of contrasted composition.

Stutzer described the intrusives as »Gangporphyre» but made no statement as to the original attitudes of the igneous masses. The available field evidence clearly suggests, however, that the present high dips of their contact surfaces are due to orogenic upturning, and that both of the porphyry bodies were initially flat-lying, sill-like, and in general concordant to bedding planes in the invaded formation. This conception is of first importance for the subsequent discussion of the ore bodies.

Eruptive Sequence in the Kiruna District.

Apart from its richness in iron ores, this region is noted for the almost unique quality of its igneous rocks, which in the main have been developed in a systematic order. They belong to a petrographic province with limits as yet undetermined, though the writings of Lundbohm, Geijer, Sundius, Zenzén, Stutzer, and others show that the principal rock types crop out in the area already studied in detail.

From oldest to youngest the larger mapped bodies (Fig. 1) were erupted in the following order: soda-greenstone (effusive), syenite-syenite porphyry (laccolith), and quartz porphyry (laccolith). Pebbles of syenite, syenite porphyry, and quartz porphyry in the Kurravaara conglomerate show that bodies of these materials were subject to erosion or else volcanic fragmentation before the laccoliths were injected. The direct sources of these pebbles are unknown and no complete statement of the eruptive sequence is yet possible. Gabbro and diabase (see Table I, Col. 1) are largely developed in the region but their relations to the soda-greenstone and porphyries are apparently unknown. The close field association of these basaltic magmas with the highly abnormal keratophyric (porphyry) magmas of the laccoliths is a fact significant for the ultimate problem as to the origin of the keratophyres themselves, but here needing no special emphasis.

The more direct answer to the question as to the origin of the iron ores must take account of the entire petrography of greenstone and porphyries. For details on this subject the reader is referred to the memoirs of Geijer and Lundbohm. Of particular importance in the ore-genesis problem is the chemical composition of each of the chief eruptive masses. This is approximately stated in Table I, which gives averages of several analyses in most cases. Since all the igneous bodies are more or less schlieric, these averages are more trustworthy than single analyses. Columns 2 to 6, inclusive, correspond to a rather perfect series: increasing in silica and alkalies; decreasing in iron oxides, magnesia, and lime. The order is that normal to successive, syngenetic intrusions of the batholithic type.

The soda-greenstone differs from the porphyries in showing advanced alteration. Its relatively high soda may be in part due to secondary albitization, as in typical spilites, though Lundbohm has concluded that »there is no reason to suppose that it [plagioclase of the greenstone] has not originally had this acid [albitic] composition».[1] He continues: »The soda-greenstones cannot be regarded as real diabases but may be considered as syenite-porphyry rocks rich in dark minerals. Within their area there are also varieties richer in feldspar, forming transitions to syenite-porphyries».[2] These expert views, together with the chemical averages and the microscopic details, indicate the high probability that the soda-greenstone and the laccolithic syenite porphyry are consanguineous. All the known facts accord with the conclusion that the syenitic rocks are intratelluric differentiates of the greenstone magma.

Even more clearly is the quartz porphyry the more acid pole of intratelluric splitting in the syenitic magma itself. The attentive reader of Geijer's monograph will find detailed proofs of that view, which here needs no elaboration except that involved in the following discussion of the ore differentiation.

Thus, if only the greenstone and porphyries are considered, it is concluded that the somewhat unusual mother magma (greenstone magma) has undergone successive splittings which have followed the general rule for a batholithic magma. Here as elsewhere the order of eruption is best explained on the assumption that the parent magma was slowly differentiated under the control of gravity. Accordingly, surface outflows or satellitic (apophysal) injections from the roof phase of the magma chamber should be successively more siliceous and less femic. Table I summarizes the fact.

---

[1] Hj. Lundbohm, Geol. Fören. Förh., Stockholm, Vol. 32, 1910, p. 756.
[2] Hj. Lundbohm, ibid., p. 758.

Differentiation of the Main Ore Bodies.

Geijer's hypothesis for the ores is best expressed in his own words (page 269):

»The *mise en place* of the Kiirunavaara-Luossavaara ores is believed by the writer to have been as follows. After the solidification of the syenitic outflow, during the period of eruption of the syenite-porphyry dikes, there have taken place eruptions of magnetite, spreading out as somewhat irregular lava beds . . .

Some reactions probably continued even after the eruption [extrusion] of the [immediately overlying] quartz-porphyry. This phenomenon, together with the existence of small ore bodies in this porphyry, makes it very probable that the eruption of the ores took place shortly before that of the rock in question. The whole time between the eruptions of the main porphyry beds seems to have been very short.»

On page 122 he writes: »The writer is therefore inclined to assume that the ore and its hanging wall rock are almost contemporaneous in their formation.»

Again, on page 266: »By their mode of occurrence the Kiirunavaara-Luossavaara ores seem to be most closely connected with their hanging wall rock, the quartz porphyry. The rock areas occurring in them, which do not seem to be fragments detached from the foot wall, are on the other hand more similar to the older, syenitic rocks. It seems to be most probable that the differentiation of the ore material has taken place before or at the same time as the separation of the mother magma in one syenitic and one quartz-bearing phase.

Now arises the question of the cause and progress of the differentiation process. Contrary to what is the case among the ores of the basic rocks, we have no deposits crystallized *in statu nascendi* at hand. Nowhere within the Kiruna region or outside it do we find the differentiation interrupted at such a stage, that the crystallized product gives any considerable information in this respect.»

In a personal letter, dated December 29, 1911, Dr Geijer indicated to the writer a certain change of view. After summarizing the field relations and also his argument for the extrusive origin of ore and porphyries, he wrote: »It is then the most probable explanation to accept the ore bodies as intermediate in age between the syenite rocks and the quartz porphyry, and, while believing these rocks to be extrusive, as superficial flows. However, further pondering over the question has led me to believe that the ore magma may have been brought to the surface as a heavy bottom part of the quartz-porphyry flow (but differentiated prior to extrusion). The mechanical details of an extrusive process of this kind can hardly be discussed, but I have failed to find any evidences against this explanation.»

A recent publication by Dr Geijer emphasizes the extrusive character of the porphyry at Ekströmsberg, with which a notable body of iron ore is »in the most intimate relation».[1] Stutzer agrees that the quartz porphyry at Ekströmsberg is extrusive. If that is true, Ekströmsberg furnishes an almost unique case of the large-scale schlieric segregation of magnetitic ore in a lava flow. Yet that fact obviously does not forbid belief in ore segregation within a similar magma which has been laccolithically injected; the writer is more inclined to believe that the main Kiruna porphyries have been thus injected. That the already differentiated quartz porphyry and ore could, as a unit, be erupted seems almost infinitely improbable, if indeed it is not a mechanical impossibility.

Their mutual transitions, their mutual diking, their relations to the older syenite porphyry, and the general body of fact described in Geijer's memoir show that the quartz porphyry and the main ore bodies are of essentially contemporaneous origin. This principal conclusion from field study has its simple and apparently sufficient explanation in the hypothesis of laccolithic splitting in place.[2] Stutzer saw the intrusive nature of the porphyries but his writings are not clear as to their relation to the ore bodies, the main point of the problem.

In the letter above noted, Geijer states that at a very early stage in his investigation he tried the hypothesis of gravitative differentiation *in situ*, »under the assumption, however, that the porphyry was extrusive». He gave it up for the following reasons: (1) »The contact between rock and ore is too sharp»; (2) »The sinking of minute magnetite crystals requires a high degree of fluidity in the magma»; (3) »Finally, a precipitate of this kind could hardly have obtained the structures that are most characteristic of the ores in question».

---

[1] P. Geijer, Förh. Geol. Fören., Stockholm, 1912, pp. 736 and 746.
[2] A. Bergeat (Fortschritte der Mineralogie, etc., Jena, Band 1, 1911, p. 148) considers this hypothesis invalid but gives no grounds for his scepticism.

The first of these arguments implies an a priori conception that the ore differentiate should normally pass into its parent porphyry through a transitional shell of mixed ore and porphyry. In fact, such a transition, in a 10-centimeter shell, actually occurs in the hanging-wall rock at the Direktören and Professorn claims of Kiirunavaara.[1] A transition on a much larger scale is illustrated at the northern end of Kiirunavaara, where the massive ore is overlain by a thick layer of porphyry heavily charged with magnetite schliers. These ore schliers carry primary feldspar phenocrysts exactly like those of the purer porphyry alongside. (Compare Fig. 4.) Thus, locally there is a real passage phase between ore and quartz porphyry. Yet in general the contact between the two is best described as sharp. What is the significance of that fact?

No one doubts that a single magnetite crystal in the quartz porphyry is a differentiate in place, though its contour is very sharp. All must agree with Geijer that his "embryonal" nodules of ore — minute aggregates of magnetite crystals — are primary segregations in the porphyries, though their contacts are sharp. Is the reasoning to be different when the segregations are larger? The answer is implied in the following discussion of the ore "inclusions" which are so abundant in the quartz porphyry. Lherzolitic, wehrlitic, and other common olivine-rich nodules in basaltic and allied rocks often reach large size and are sharply bounded; yet their expert students are now largely convinced that these nodules are segregations nearly or quite *in situ*.

The statement that the ore bodies could not be due to the settling-down of minute magnetite crystals may conceivably be accepted by all petrologists. The settling of large groups of crystals or of globules of liquid ore is, however, a different matter. As usual the question is as to the unit of differentiation. Only when the nature and size of that unit are known is it possible to estimate the speed and final extent of segregation. As soon to be noted, several lines of evidence lead to the conclusion that the unit of differentiation was, in reality, of considerable size, insuring rapid settling and segregation of iron ore. Meantime, it suffices to remark that it is unsafe to assume that the unit must be a minute crystal.

Geijer's third argument is also affected by an assumption as to the unit of differentiation. The peculiar structures of the Kiruna ores are certainly connected with the abnormal chemistry of the magmas erupted in

[1] P. Geijer, Igneous Rocks and Iron Ores of Kiirunavaara, etc., 1910, p. 119. Cf O. Stutzer, Neu. Jahrb. für Mineralogie, etc., B. B. 24, 1907, p. 606.

the district. The unusual order of crystallization in the ores offers no specially difficult problem if the unit of differentiation was a non-consolute, liquid portion of the porphyry magma.

In conclusion, the writer believes that there is much to be said for Geijer's own early hypothesis of gravitative settling. Whether the segregation took place in a thick lava flow or in a laccolithic chamber is not so important in the ore-genesis problem, though settling could obviously continue much longer and account for a larger segregation in a laccolith than in a lava flow, quickly chilled by radiation.

Ore »Inclusions» in the Quartz Porphyry.

If there is any one point which is crucial, it is the true explanation of the ore »inclusions» in the quartz porphyry. These were long ago noted by Lundbohm and have won the special attention of all geologists visiting Kiruna. Outcrops are wanting over most of the porphyry body but Geijer appears to be right in his generalization that the ore inclusions are most numerous toward the floor of the porphyry. Nevertheless, the writer has found them close to its upper contact and no part of the body can be assumed to be entirely free from ore inclusions. In general, they are small, seldom over 10 centimeters in diameter. A very few have been recorded with diameters of 30 to 40 centimeters. Many are round; many others are angular. Macroscopically most of them are seen to be sharply bounded against the enclosing porphyry; but some have forms and relations suggesting gradation into schliers or acknowledged segregations.

Concerning the origin of the more definite »inclusions», Geijer writes (pages 156—7 of his memoir); »The fragments probably originate from a larger ore mass which in composition and structure must be similar to the ores of Kiirunavaara and Luossavaara. It is quite impossible that these numerous fragments should be as many concentrations of the magnetite and apatite content of the quartz-porphyry; even when leaving other features out of question, we see that their very shape is irreconcilable to such a supposition. On the other hand they can of course not be *proved* to originate from the ore zone of the two mountains just mentioned, even if this seems to be rather probable. Their distribution is simply explained by the hypothesis that the quartz-porphyry at the eruption has broken through an ore mass somewhere in the neighbourhood of south Luossajärvi, and the part containing fragments of it had then during the outflow of the porphyry extended and assumed its present shape; the explanation will be analogous under the supposition that the quartz-porphyry should have flowed out from a long fissure.

In December, 1912, Geijer issued a supplementary paper containing the following passage: »It is the presence of ore fragments in the quartz-porphyry that forms the main footing for this hypothesis of a surface flow of ore magma. Let it only be remembered here, that these fragments generally are sharply defined, sometimes angular, and that they represent nearly all ore types of Kiirunavaara, fragments of various types often being found together. These fragments cannot be basic segregations from the surrounding rock, they must come from an ore body petrographically identical to the Kiirunavaara-Luossavaara ores and cut through by the quartz-porphyry.»[1]

Stutzer similarly concluded that the presence of these »inclusions» proves the quartz porphyry to be younger than the main ore bodies.[2]

Lundbohm is more cautious, remarking: »A satisfactory explanation of this fact [the existence of the ore »inclusions»] does not seem yet to have been found, but it is evident that it ought to be taken into serious consideration when discussing the origin of the iron ore and the surrounding rocks.»[3]

If the »inclusions» were thus mechanically derived from the main ore bodies, an important consequence is at once deducible. Many of them are now hundreds of meters above the floor of the porphyry mass. At the time they were included, the density of the magma was considerably less than that of the porphyry now, while that of each solid xenolith was only very slightly less than now. Their respective specific gravities must have been approximately 2,4 and 4,9. That the xenoliths have remained at all levels, even to that nearly one kilometer vertically above the base of the porphyry, must mean that the viscosity of the magma was practically infinite when the fragments were included. Such a magmatic condition at the moment of eruption is incredible in the case of the Kiruna porphyries; to the writer this difficulty is insuperable for the xenolithic hypothesis.

Geijer concludes that »contrary to what is the case among ores of the basic rocks, we have no deposits crystallized *in statu nascendi* at hand»,

[1] P. Geijer, Förh. Geol. Fören., Stockholm, Vol. 34, 1912, p. 774.
[2] O. Stutzer, Neu. Jahrb. für Mineralogie, etc., B. B. 24, 1907, p. 567.
[3] H. Lundbohm, Förh. Geol. Fören., Stockholm, Vol. 32, 1910, p. 772.

adding, however, »Some hints might be obtained only from the ore dikes and schlieren of the quartz-porphyry of Kiirunavaara, etc.».[1] He concedes that there are »embryonal» nodules and even well developed nodular and schlieric segregations of ore in the syenite porphyry, the main quartz porphyry, the »magnetite-syenite porphyry», and the Tuolluvaara quartz porphyry.[2] Moreover, the present writer has observed all transitions from single magnetite crystals, through microscopic »embryonal» nodules or lumped aggregates of such crystals, to the large, rounded and angular »inclusions», conspicuous in ledge and hand-specimen. So gradual is this transition and so perfectly do the large »inclusions» agree in composition with the obviously non-xenolithic aggregates, that the writer is compelled to regard these »inclusions» as the actual units of differentiation, or else their partial remnants. If so, these units came out of the magmatic solution just as its final consolidation took place, the nearly infinite viscosity at that stage preventing their sinking to the laccolithic floor. They are the frozen-in equivalents of the millions of units which did sink to the floor, to form the main ore bodies, during the long preceding period of higher temperature and lower viscosity.

At first sight it may appear difficult to accept such an explanation of the distinctly *angular* »inclusions». As already stated, their angularity has specially prompted the hypothesis that the isolated ore masses are foreign fragments. If all the »inclusions» were round, the observer would be more likely to stress their analogy with the olivine nodules of basaltic rocks, with basic seggregations in granite, syenite, or diorite, or even with the orbules of orbicular granites, diorites, etc. However, it is important to examine the thesis that some truly endogenous »inclusions» should have angular and sharp outlines against their enclosing matrices.

There can be no question of the *fact*, in the case of various types of generally recognized basic segregations. Every thorough student of those in the plutonic rocks is familiar with sharply angular, or at least very irregularly shaped, segregations associated with chemically similar round ones; and in general he sees no reason to doubt their common origin as truly endogenous growths. Examples familiar to the writer have been described at Ascutney Mountain, Vermont.[3] In other New England granites and in

---

[1] P. Geijer, Igneous Rocks and Iron Ores of Kiirunavaara, etc., 1910, p. 266.
[2] P. Geijer, ibid., pp. 9, 17, 21, 30, 32, 35, 37, 40, 53, 62, 64, 150, 151, 183, 191, 203, and 207.
[3] R. A. Daly, Bull. 209, U. S. Geological Survey, 1903, plates V and VI. Cf. F. Zirkel, Lehrbuch der Petrographie, Leipzig, Vol. 2, 1894, pp. 931 and 934.

various Cordilleran granites similar cases have been observed. Many olivine nodules in basalts are angular or irregular in form. Equally telling are the many instances of angular and irregular lumps of ore or hornblende in the various Kiruna porphyries, described by Geijer as endogenous growths or segregations in place.[1]

Confidence in the thesis is further strengthened by an analysis of the different causes for the angular or irregular form characterizing true segregations in place or nearly in place.

As noted above, many of the recognized ore segregations are more or less angular from their birth and still preserve their original forms.[2] This

Figure 3.

is surely true of the »embryonal» nodules and of numerous ore schliers in the porphyries (Fig. 3).

However, there is good field evidence that angular form and sharp contacts have been commonly developed by secondary, late-magmatic processes. The latter were both mechanical and chemical in nature.

Some of the ore nodules, like many basic segregations in granites, syenites, etc., have been formed and then (probably after their complete

[1] See above, and compare Fig. 9 on page 23 of Geijer's memoir.

[2] Very many of the nodular »inclusions» and even some of the angular »inclusions» are enclosed in light-colored, feldspathic shells (Hofs) which are abnormally poor in disseminated magnetite, as if iron ore had been locally abstracted from the host, to form, or increase the size of, the »inclusions».

crystallization) split asunder by thin, dike-like tongues of the mother magma. This splitting invariably means added angularity for each part of the divided nodule. Though the viscosity of the mother magma may be very high, it cannot be infinite. All the fragments of the now divided nodule must slowly sink. The rate of fall being directly proportional to the square of the radius, the larger fragments must sink faster than the smaller: they will thus be separated. Some of these angular fragments may be frozen-in before reaching the floor of the laccolith.

Again, the mechanical splitting of nodules and the isolation of fragments is evidently possible if the laccolithic magma, extremely viscous because of imminent crystallization, is affected by shearing stresses sufficient to break ore nodule or schlier.

Study of igneous rocks in nature and of experimental melts have proved that resorption of crystals early formed in a melt, is exceedingly common.[1] Perfect chemical equilibrium is probably never reached in the crystallization of a natural magma. Partial resorption of quartz phenocrysts in ordinary quartz porphyry, of olivine phenocrysts in olivine basalts, and of hornblende or pyroxene phenocrysts in many porphyritic dike and volcanic rocks, is a familiar phenomenon. Resorption has clearly affected basic silicate segregations in plutonic rocks. According to the writer's observations, it has similarly changed (often made more angular) the original outlines of the ore »inclusions» in the Kiruna porphyries. Illustrations are represented in Figure 4. Some ore nodules show merely shallow bays filled with the porphyry ground-mass. Others are so deeply embayed that each nodule is almost divided into two or more parts. In both cases the original form is made more angular, while the sharpness of contact has been retained or rendered yet more perfect.

Faith in the reality of this process is not shaken by one's ignorance of its physico-chemical cause. It was doubtless connected with the evolution of latent heat in early crystallization; with the necessary chemical changes in the mother magma as crystallization progressed; and with the accidental variations in the distribution of volatile matter in the residual melt. Considering the chemistry of the system here involved, it seems highly pro-bable that extensive resorption of the ore segregations should have taken place.

If such re-solution proceeds to the point of dividing a nodule into two or more parts, these also may sink differentially and so be separated.

---

[1] Cf. F. Rinne, Fortschritte der Mineralogie, etc., Jena, Band 1, 1911, p. 197.

Hence for several reasons the angular forms of visible ore »inclusions» cannot be taken to prove their xenolithic origin.

It is also clear that their sharp contacts against the enclosing porphyry affords no valid argument against their endogenous origin. In part the sharpness of contact may be due to the surface tension between the two substances, ore and mother magma (non-consolute at the moment of segregation of the ore). Geijer agrees that some direct segregations (nodules) of ore in the Kiruna porphyry are »rather sharply separated from the mother rock».[1] The mutual contact *must* be sharp if each nodule or fragment of

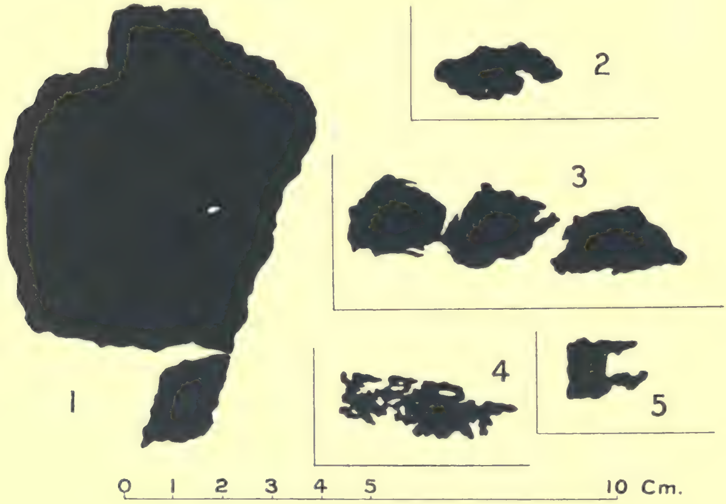

Figure 4.

a nodule has sunk somewhat below the level of its original segregation. Clearly shells of transition are not to be expected when the slowly sinking »inclusion», now contacting with successive layers of magma, is finally frozen-in, for then the viscosity is almost infinite and interaction must be very slight or nil.

In view of so many possibilities, if not certainties, the angularity and contact relations of the ore »inclusions» cannot be safely regarded as disproving their autochthonous origin.

The xenolithic hypothesis has other special difficulties. One is the fact that the »inclusions» are all comparatively small, seldom surpassing 10

[1] P. Geijer, Förh. Geol. Fören., Stockholm, Vol. 34, 1912, p. 782.

cm. in diameter and never, so far as known, surpassing 40 cm. There is no apparent reason why xenoliths should be so restricted in size, though such limitation is the rule for basic segregations in general.

To be thoroughly convincing, the xenolithic hypothesis must account for the source of the ore fragments. Geijer was forced to postulate an invisible ore body, older than the quartz porphyry, as the source. Other observers have hastily concluded that the ore fragments were broken off from the visible, main ore bodies by the younger quartz porphyry magma. The latter view is negatived by the facts showing the essential contemporaneity of porphyry and main ore bodies, e. g., their mutual diking. Geijer's summary will recall the essential facts. He writes on page 122 of his memoir): »Farthest south we find phenomena indicating that the ore is younger than the quartz-porphyry. Some features of northern Kiirunavaara and Luossavaara favour such a view, but the occurrence of the numerous inclusions of ore, originating from a petrographically quite similar ore deposit, are against it. The writer is therefore inclined to assume that the ore and its hanging wall rock are almost contemporaneous in their formation.» Stutzer is one of those holding to the xenolithic hypothesis but he was compelled to make the assumption »einer gewissen Gleichzeitigkeit» between ore and quartz porphyry. He vaguely adds: »Als der hangende Keratophyr aufstieg, war der Magnetit erst zum Teile erstarrt, wurde mitgerissen und vollständig auskristallisiert.»[1] Two pages farther on in his paper, Stutzer writes his general conclusion as follows: »Die Magnetite der Umgegend von Kiruna hängen genetisch aufs engste mit den sie begleitenden Keratophyren zusammen. Wie die Porphyre sind sie auf magmatischem Wege entstanden, und relativ gleichzeitig mit diesen nach oben durchgestossen.»

To the hypothesis of an older invisible ore body, large enough to supply xenoliths to practically *all* parts of the huge quartz prophyry mass, there are several objections, in part already suggested. The hypothesis gives no explanation of the wide distribution of the »inclusions», nor of their suspension at the observed high levels in the laccolith. Perhaps yet more convincing is the rarity of xenoliths of syenite porphyry in the quartz porphyry. If millions of xenoliths were torn off from an older ore body, necessarily of very small relative size, it would seem inevitable that numerous enclosures of the vastly thicker and more extensive syenite porphyry should be made. In the field the writer was much struck with the almost entire

[1] O. Stutzer, Neu. Jahrb. für Mineralogie, etc., B. B. 24, 1907, p. 606.

absence of such xenoliths in the younger porphyry. He did not see a single one in all the upper, much the greater, part of the younger laccolith, even where ore »inclusions» were comparatively abundant. The failure of syenitic xenoliths to appear at the upper levels cannot be ascribed to their settling down because of their superior density, without implying that the much denser ore »inclusions» at the horizons in question are of non-xenolithic origin.

Novel and delicate as the problem is, the writer has been forced to take the view that the ore »inclusions» represent so many frozen-in units of differentiation, many of which, however, have been modified in form by resorption and other late-magmatic processes.

Concentration of the Units of Differentiation.

Considering the relative densities of ore nodule and mother magma, it must be admitted that such units, formed during the long period of moderate magmatic viscosity, would sink all the way to the floor of the laccolith. They must have so sunk even if the viscosity approached that of hard pitch. Probable as the liquation theory is in this case, it is impossible to be sure that the nodules represent so many non-consolute fractions of the original magma. Yet the main ore bodies were certainly at least in part molten when they sent apophysal dikes into the underlying syenite porphyry and brecciated it. A few, thin apophyses cut the quartz porphyry, showing that at least some of each main ore body was still liquid when the overlying silicate melt had already stiffened enough to be diked.

Once more it may be recalled that these ore dikes do not prove any lack of essential contemporaneity between the quartz porphyry and the ore.[1] The two magmas may have been of absolutely synchronous origin and yet one, longer fluid, may dike the other when crystallized or rendered very viscous by cooling. Neither field observation nor experimental study can yet decide as to which of the two bodies would crystallize first at the bottom of the great laccolith. From microscopic evidence Geijer concluded that »the magnetite and the apatite, the two main constituents of the ore, are disposed to separate from the rest of the rock and are in solution longer than the latter.»[2] Hence, so far as masterly petrographic research

[1] Cf. page 150 of Geijer's memoir.
[2] P. Geijer, Igneous Rocks and Iron Ores of Kiirunavaara, etc., 1910, p. 267.

can now furnish the data, it is justifiable to hold that the ore bodies remained fluid, at least in part, after the bottom layer of the quartz porphyry became stiffened to the point of being capable of rather clean-cut fissuring.

Inspection of the map shows the Kiruna ore bodies to be located where they should be if they are due to settling-out from the quartz porphyry (Fig. 1). They are on the floor of that uptilted laccolith and thicken towards the middle of its length as measured along the outcrop. Notwithstanding some obscurity produced by orogenic deformation, the ore bodies appear to lie in the deeper pockets of the floor which lay originally flat or nearly flat. One is reminded of the analogous case at Sudbury, Ontario, where the large sulphide bodies occur in bay-like depressions in the floor of the Sudbury intrusive sheet.[1]

A few years ago geologists would have been less ready than now to accept the idea of the gravitative separation of metallic ores in visible laccolithic chambers or intrusive sheets. The demonstrated or highly probable cases in the Sudbury sheet, in the Mount Insizwa (South Africa) sheet, in the enormous Transvaal laccolith, in the Duluth gabbro laccolith, in the several platinum-bearing laccoliths of the Ural mountains — respectively described by Barlow, Coleman, and Walker, by du Toit, by Molengraaff, and by Duparc and Wyssotzky, show that under certain conditions, metallic elements, their sulphides, or their oxides may be thus concentrated. The same principle is seen in the separation of denser and lighter silicates in many other sheets and laccoliths.[2]

Comparison of the Syenitic and Quartz Porphyry Magmas.

The chemical averages of Table I suggest that the regional differentiation of the Kiruna magma was progressive. The time interval between the eruptions of the syenite porphyry and quartz porphyry was at least long enough for the consolidation of the syenite porphyry laccolith. During that interval the syenite porphyry magma residual in the abyssal magma chamber should have been differentiated somewhat. The abundant hornblendic nodules in the visible syenite porphyry show a tendency toward a separation of lime, magnesia, and some iron oxide from this magma. If

[1] A. P. Coleman, Journal of Geology, Vol. 15, 1907, p. 767.
[2] R. A. Daly, Igneous Rocks and Their Origin, New York, 1914, p. 229.

the material of such a basic pole were segregated by gravity in the abyssal chamber, the remaining liquor should approach the quartz porphyry in composition, though differing from it also because of the later settling-out of the main ore bodies.

A comparison of the average amounts of iron oxides in the rocks, coupled with an estimate of the relative masses of the ore-bodies and quartz porphyry, shows that the assumption of the differentiation in place is justified on the quantitative side. The total area of the iron ore in Kiirunavaara and Luossavaara is close to 500,000 square meters. The total area of the main quartz porphyry is about 18 square kilometers. If each of these bodies be regarded as of volume equal to the figure generated by revolving the plane of outcrop about a line drawn through the middle of the laccolith and at right angles to its floor, the ore may be calculated to have a volume about 1 per cent. of that of the porphyry. The total weight of the main ore bodies would thus be about 2 per cent of the total weight of the laccolith. Compare Table II.

Table II, showing weight percentages of iron oxides in average analyses.

	Average for soda-greenstone.		Average for main syenitic body.		Average for main quartz porphyry body.	
Fe_2O_3	3,15	12,14	5,56	8,10	3,33	4,85
FeO	8,99		2,54		1,52	

The difference in the average ferric contents of the syenitic and quartz porphyry laccoliths is of the order required if the main ore bodies and the quartz porphyry were differentiated from a magma somewhat like the syenitic. The hypothesis of laccolithic splitting in place is thereby rendered all the more credible.

Distribution of Densities in the Two Laccoliths.

If gravity has segregated the workable ores, one might expect that force to have affected also the more siliceous parts of the porphyry magmas. There is some evidence of this in the distribution of rock varieties in cross-sections of each laccolith. The basal syenite of the western body is apparently more femic than the overlying syenite porphyry phase (See Table I, Cols. 3 and 4). Ore nodules, ore schliers, and disseminated magnetite crystals seem, on the whole, to be more abundant at the lower horizons of the quartz porphyry than at the higher. However, on account of the lack of continuous exposures and because of the schlieric condition of each laccolith, sufficient sampling is now impossible. All that can be definitely stated is that the field facts collected by the writer and by Geijer seem to permit the tentative conclusions just mentioned; each laccolith appears to be roughly stratified according to density.

Special Conditions for the Development of the Kiruna Ore Bodies.

The profound problem as to the original source of the iron in the syenitic magma will not here be discussed. That this type of magma has had a peculiar history is registered in the special petrography of the porphyries and in the fact that syenitic rocks of the Kiruna habit are, so far as known, restricted to Sweden and one district in the Ural mountains. The abnormality of these magmas, so rich in magnetite and apatite, is a partial reason for the rarity of the kind of ores occurring at Kiruna, at Ekströmsberg, at Gellivare, in the northern Urals, etc.

A final point remains to be noted. If the syenitic rocks approximately represent a magma from which the ores have been differentiated, why are there great segregations in the quartz porphyry laccolith, while none is known or is likely to be found in the older syenitic laccolith? A full answer to this question would involve both physical and chemical conditions of great complexity. One suggestion may be offered. All observers agree that the two porphyry bodies are not very far apart in their dates of eruption. If the older body, though solidified, was still hot when the quartz porphyry was erupted upon it, that heat would delay the chilling and consolidation of the younger body. (See Fig. 1.) A specially long magmatic life must favor large volume for the differentiated fractions if there is a tendency to split at all. In brief, the size of the Kiruna ore deposit may be unique because it has formed in the younger member of a *composite* laccolith.

Summary.

The chief purpose of this paper is to emphasize a new point of view regarding the »inclusions» of ore in the Kiruna quartz porphyry. Their origin is now clearly the core of the genetic problem of the main ore bodies. Short as the writer's field study of them has been, the data collected seem to warrant belief in the endogenous nature of nearly or quite all of the visible »inclusions«. That conclusion has been greatly facilitated by a study of the memoirs of Geijer, Lundbohm, and Stutzer. Their publications are at once so detailed and so objective in stating facts that they safely extend the scientific vision of anyone who has even a limited field knowledge of the Kiruna region. A new interpretation of some of the facts is here offered largely because of the writer's confidence in the essential soundness of these older publications.

Geijer and Stutzer do not agree as to the extrusive or intrusive character of the porphyries; field observations at visible contacts have forced the present writer to take Stutzer's view, though it is possible that the quartz porphyry intrusion locally broke through to the earth's surface. The field facts seem to accord best with the conception that the syenitic and quartz porphyry bodies are the two parts of a composite laccolith, injected into a great bedded, chiefly volcanic, series of older rocks. The injection mechanically divided that series into two parts, the Kurravaara and Hauki complexes.

The ore »inclusions« in the quartz porphyry are regarded as frozen-in units of differentiation. The gravitative assemblage of similar units at the floor of the laccolithic mass is concluded to be the direct origin of the main ore bodies. This view is closely similar to Geijer's unpublished, because abandoned, hypothesis of ore formation, though he was then thinking in terms of an extrusive relation for the porphyry.

The discussion is not detailed as to general grounds for belief in the magmatic differentiation of the ores. That basal postulate is now generally accepted by competent students of the Kiruna district. However, emphasis is here placed on the eruptive sequence and on the chemical composition of the porphyries as indicating the validity of the magmatic theory and particularly the theory of ore differentiation in place.

The special topics treated are: The contact relations of quartz porphyry and main ore bodies; the position of those bodies at the floor of the quartz porphyry laccolith; the origin of the angularity and sharp individuality of many ore »inclusions« in the quartz porphyry; the necessary considerations as to relative densities; analogies in other intrusive laccoliths and sheets; and the peculiar chemical and physical conditions which have made possible the almost unique amount of ore segregation shown at Kiruna.

The hypothesis of laccolithic differentiation *in situ* is herewith offered for debate by those who know the district best. Whatever be the ultimate fate of this suggestion, there is no doubt that all petrologists should keep their eyes fastened on the Kiruna ore bodies as, in many respects, peerless examples of the differentiation of oxides from igneous magmas.

VETENSKAPLIGA OCH PRAKTISKA UNDERSÖKNINGAR I LAPPLAND

ANORDNADE AF LOUSSAVAARA—KIIRUNAVAARA AKTIEBOLAG:

Geology:

1 a. HJALMAR LUNDBOHM, Sketch of the Geology of the Kiruna District.
1 b. A. G. HÖGBOM, The Gellivare Iron Mountain.
2. PER GEIJER, Igneous Rocks and Iron Ores of Kiirunavaara, Luossavaara and Tuolluvara.
3. OTTO SJÖGREN, Bidrag till Kirunaområdets Glacialgeologi.
4. NILS SUNDIUS, Beiträge zur Geologie des südlichen Teils des Kirunagebiets.
5. REGINALD A. DALY, Origin of the Iron Ores at Kiruna.
6. V. CARLHEIM-GYLLENSKÖLD, Magnetic Survey of the Iron Ore Field of Kiirunavaara.

Flora and Fauna:

1. HERMAN G. SIMMONS, Floran och Vegetation i Kiruna.
2. THORE C. E. FRIES, Botanische Untersuchungen im nördlichsten Schweden.
3. SVEN EKMAN, Om Torneträsks Röding, sjöns naturförhållanden och dess fiske.

Social Hygiene:

1 a. GUSTAF NEANDER, Tuberkulosens utbredning bland befolkningen i Kiruna.
1 b. GUSTAF NEANDER, Fréquence de la Tuberculose parmi la Population de Kiruna. (Traduction).
2. GUSTAF NEANDER, Kaptensgårdens Sanatorium, Malmberget.

STOCKHOLM 1915. KUNGL. BOKTRYCKERIET. P. A. NORSTEDT & SÖNER. 150965

3|10|01

QE 381 F5D35

Daly, Reginald Aldworth
Origin of the iron ore
Kiruna

Physical & Applied Sci.

PLEASE DO NOT REMOVE
CARDS OR SLIPS FROM THIS POCKET

UNIVERSITY OF TORONTO LIBRARY